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BALLPARK RELIABILITY ESTIMATION TECHNIQUES

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This report analyzes data obtained from the RADC Computer Program ORACLE, a program which performs failure rate predictions of electronic equipment according to MIL-HDBK-217, in order to develop a "ballpark" failure rate estimation technique. Simplified formulas based on average parameters provided by the data and an average failure rate per part are developed to provide a fast and easy method to approximate the reliability of electronic systems.

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BALLPARK RELIABILITY ESTIMATION TECHNIQUES

I. INTRODUCTION

In the preliminary phases of a design when detailed information about individual components making up a system is unavailable, a method for obtaining a general estimate of reliability magnitude would be both helpful and desirable as a prelude to the more detailed Parts Count Prediction Technique performed in accordance with MIL-HDBK-217. Such an estimate has the capability to provide visibility as to whether or not the contemplated design makeup has the potential of meeting end item reliability requirements early in the design cycle and can also provide necessary inputs to the reliability allocation process at that time.

The purpose of this study is to examine the feasibility of developing a "ballpark" failure rate prediction technique based on (1) environment and average stress factors for each common part type and ultimately, (2) average failure rate per part. These average factors would be determined from data provided by six different electronic equipment reliability predictions performed using the RADC Computer Software Package ORACLE which automates the performance of a detailed failure rate prediction in accordance with MIL-HDBK-217. Ref. is made to MIL-HDBK-217D which defines the basic failure rate equations used in this study and to Appendix A of this report which defines the part type codes used as identifiers in various tables in the report.

II. FAILURE RATE RESULTS

Six arbitrary electronic communications equipments were utilized as prediction vehicles with the following specifications:

SYSTEM	NO. OF PARTS	ENVIRONMENT	AMBIENT TEMPERATURE
A	1308	Ground Fixed	$51^{o}C$
B	1376	Naval Sheltered	$40^{o}C$
C	320	Ground Mobile	$52^{o}C$
D	1579	Naval Sheltered	$40^{o}C$
E	5721	Airborne Uninhabited Flight	$68^{o}C$
F	844	Ground Fixed	$40^{o}C$

Failure rate data for the six systems were collected and analyzed* according to part type as follows:

a. Capacitors

The basic failure rate as described in MIL-HDBK-217 is given by:

$$\lambda_p = \lambda_b \left(\Pi_E \times \Pi_{CV} \times \Pi_{SR} \times \Pi_Q\right)$$

where

λ_p = failure rate (failures/10^6 hours)

λ_b = base failure rate

Π_E = environmental factor

Π_{CV} = capacitance factor

Π_{SR} = series resistance factor

Π_Q = quality factor

*Ref. Appendix B for a detailed breakdown of component part types and their associated failure rates for each of the six electronic systems analyzed.

Isolating the environment factor (Π_E) yields:

$$\lambda_p = \Pi_E\ (\lambda_b \times \Pi_{CV} \times \Pi_{SR} \times \Pi_Q)$$

defining

$$C = (\lambda_b \times \Pi_{CV} \times \Pi_{SR} \times \Pi_Q)$$

yields:

$$\lambda_p = \Pi_E\ C$$

Utilizing the data from the six prediction vehicles, an average "C" value for each of 2,594 capacitors was calculated. Averaging all of the "C" values yielded:

$$C_{av} = .0026$$

Using C_{av} as an estimator of C in the above formula:

$$\lambda_p = .0026\ \Pi_E$$

Also, since Π_E factors vary according to capacitor style, the following table shows the average value over all capacitor styles for each environment and should be used in the above formula:

ENVIRONMENT*	Π_E
G_B	1
S_F	1
G_F	2.5
N_{SB}	5.5
N_S	6.4
A_{IT}	5.7
M_P	11.8
M_{FF}	11.5
M_{FA}	15.9
G_M	9.2
N_H	17.8
N_{UU}	19.1
A_{UT}	19.9
N_U	15.1
A_{IF}	11.4
A_{RW}	25.6
U_{SL}	33.4
A_{UF}	39.9
M_L	38.3
C_L	66.8

*See MIL-HDBK-217D for definition of each environmental factor.

b. Resistors

The basic formula for resistors is:

$$\lambda_p = \lambda_b (\Pi_E \times \Pi_R \times \Pi_Q)$$

where:

λ_p = failure rate (failures/10^6 hrs)

Π_E = environmental factor

Π_R = resistance factor

Π_Q = quality factor

λ_b = base failure rate

Isolating Π_E and defining $R = \lambda_b \times \Pi_R \times \Pi_Q$

yields:

$$\lambda_p = \Pi_E R$$

Utilizing the data from the six prediction vehicles, an average "R" value for each of 2,563 resistors was found. Averaging all of the "R" values yields:

$$R_{av} = .004$$

Using Rav as an estimator of R in the above equation:

$$\lambda_p = .004 \Pi_E$$

Since the Π_E factors vary according to resistor style, the following table shows the average value over all resistor styles for each environment. These Π_E factors should be used in the above formula.

ENVIRONMENT	π_E
G_B	1.0
S_F	1.0
G_F	2.4
N_{SB}	5.8
N_S	6.0
A_{IT}	4.4
M_P	14.4
M_{FF}	13.8
M_{FA}	19.5
G_M	10.8
N_H	22.1
N_{UU}	23.6
A_{UT}	11.9
N_U	14.7
A_{IF}	8.9
A_{RW}	28.1
U_{SL}	37.4
A_{UF}	23.6
M_L	47.2
C_L	797.5

c. The basic model for discrete semiconductors is:

$$\lambda_p = \lambda_b (\Pi_E \times \Pi_A \times \Pi_Q \times \Pi_R \times \Pi_{S2} \times \Pi_C)$$

where:

λ_p = failure rate (failures/10^6 hrs)

λ_b = base failure rate

Π_E = environmental factor

Π_A = application factor

Π_Q = quality factor

Π_R = power rating factor

Π_{S2} = stress factor

Π_C = construction factor

Isolating the Π_E and defining

$$D = \lambda_b \times \Pi_A \times \Pi_Q \times \Pi_R \times \Pi_{S2} \times \Pi_C$$

yields:

$$\lambda_p = \Pi_E D$$

(1) Diodes

Utilizing the data from the six prediction vehicles containing 748 general purpose and zener diodes yielded an average "D" value of:

$$D_{av} \text{ (diodes)} = .0016$$

Using D_{av} (diode) as an estimator of D in the above formula:

$$\lambda_p = .0016 \, \Pi_E$$

If the particular type of diode is known (i.e., general purpose, zener, etc.), use the specific Π_E factor for that style. Otherwise, use the Π_E factor for Group IV General Purpose diodes. (Ref. Table 5.1.3.4-1 of MIL-HDBK-217D)

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(2) Transistors

Utilizing the data from the six prediction vehicles containing 152 transistors yielded:

D_{av} (transistor) = .008

Using D_{av} (transistor) as an estimator for D in the above formula:

$\lambda_p = .008\ \Pi_E$

If the specific type of transistor is known, use the Π_E factor for the particular part. Otherwise, use the Π_E factor for Group I transistors. (Ref. Table 5.1.3.1-1 of MIL-HDBK-217D)

d. Relays

The general failure rate model given in MIL-HDBK-217D is:

$$\lambda_p = \lambda_b (\Pi_E \times \Pi_C \times \Pi_{CYC} \times \Pi_F \times \Pi_Q)$$

where:

λ_p = failure rate (failures/10^6 hrs)

λ_b = base failure rate

Π_E = environment factor

Π_C = contact form factor

Π_{CYC} = cycling factor

Π_F = failure rate factor (application & construction)

Π_Q = quality factor

Isolating Π_E and defining:

$$RY = \lambda_b \times \Pi_C \times \Pi_{CYC} \times \Pi_F \times \Pi_Q$$

yields:

$$\lambda_p = RY\ (\Pi_E)$$

There were 44 Relays in the six prediction vehicles utilized. For each relay, an "RY" value was calculated, and an average value of RY was determined to be:

$$RY_{av} = .069$$

Using RY_{av} as an estimator of RY yields:

$$\lambda_p = .069\ \Pi_E$$

Ref. Table 5.1.10-4 of MIL-HDBK-217D for Π_E values.

---

e. Integrated Circuits

The basic formula for the failure rate (λ_p) of an integrated circuit is:

$$\lambda_p = \Pi_Q\ (C_1\Pi_T\Pi_V + (C_2 + C_3)\ \Pi_E)\ \Pi_L$$

where:

λ_p = failure rate (failures/10^6 hrs)

Π_Q = quality factor

Π_T = temperature acceleration factor

Π_V = voltage derating stress factor

Π_E = application environmental factor

Π_L = device learning factor

C_1 & C_2 = circuit complexity failure rates (based on gate count)

C_3 = package complexity failure rate (based on pin count)

Since the range of Π_Q values in MIL-HDBK-217 is from .5 to 35, and is a prime contributor to the overall failure rate, Π_Q as well as Π_E will be isolated, and the following defined:

$$A = C_1 \Pi_T \Pi_V \Pi_L$$

and

$$B = (C_2 + C_3)\Pi_L$$

Utilizing data from the six prediction vehicles containing 1955 integrated circuits, yielded average values of "A" and "B" of

$$A_{av} = .047$$

and

$$B_{av} = .0024$$

Using A_{av} and B_{av} as estimates of A and B in the above formula yields:

$$\lambda_p = \Pi_Q\ (.047 + .0024\ \Pi_E)$$

If Π_Q is unknown, assume b-1 quality level (therefore $\Pi_Q = 3.0$) and the formula becomes:

$$\lambda_p = .140 + .007\ \Pi_E$$

Ref. Table 5.1.2.5-3 of MIL-HDBK-217D for the Π_E values.

---

f. Inductors

The basic failure rate model for inductive devices in MIL-HDBK-217D is given by:

$$\lambda_p = \lambda_b \, (\Pi_E \times \Pi_Q \times \Pi_C)$$

where:

λ_p = failure rate (failures/10^6 hrs.)

λ_b = base failure rate

Π_E = environmental factor

Π_Q = quality factor

Π_C = construction factor

Isolating Π_E and defining:

$$I = \lambda_b \, \Pi_Q \Pi_C$$

yields:

$$\lambda_p = I \, \Pi_E$$

Due to a lack of data in the six prediction vehicles, (only putting 15 data points) a representative parts count value for "I" based on available data and engineering judgement was developed such that:

$$I = .0009$$

Therefore,

$$\lambda_p = .0009 \, \Pi_E$$

Ref. Table 5.1.8.2-3 of MIL-HDBK-217D for Π_E values.

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g. Connectors

The failure rate model for a mated pair of connectors is given by:

$$\lambda_p = \lambda_b \, (\Pi_E \times \Pi_p \times \Pi_k)$$

where

λ_p = failure rate (failure/10^6 hrs.)

λ_b = base failure rate

Π_E = environmental factor

Π_p = failure rate multiplier

Π_k = mating/unmating factor

For the failure rate of a single connector, divide λ_p by 2. Isolating the Π_E, and defining:

$$N = \lambda_b \times \Pi_p \times \Pi_k$$

yields:

$$\lambda_p = N \, \Pi_E$$

Utilizing the data from the six prediction vehicles containing 103 connectors, an "N" value was calculated for each, and an average value of N was determined to be:

$$N_{AV} = .021$$

Using N_{AV} as an estimator of N yields:

$$\lambda_p = .021 \, \Pi_E$$

Ref. Table 5.1.12.1-6 of MIL-HDBK-217D for Π_E values.

---

h. Optical Devices

The part failure rate model for opto-electronic semiconductor devices is given by:

$$\lambda_p = \lambda_b \, (\Pi_T \times \Pi_E \times \Pi_Q)$$

where:

λ_p = failure rate (failures/10^6 hrs.)

λ_b = base failure rate

Π_T = temperature factor

Π_E = environmental factor

Π_Q = quality factor

Isolating Π_E and defining:

$$P = \lambda_b \times \Pi_T \times \Pi_Q$$

yields:

$$\lambda_p = P\ \Pi_E$$

Again, due to a lack of data in the six prediction vehicles, (only 16 data points), a representative parts count value for "P", based on available data and engineering judgement, was developed such that:

$$P = .07$$

Therefore,

$$\lambda_p = .07\ \Pi_E$$

Ref. Table 5.1.3.10-1 of MIL-HDBK-217D for Π_E values.

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i. Switches

The failure rate model for switches is given by:

$$\lambda_p = \lambda_b\ (\Pi_E \times \Pi_C \times \Pi_{CYC} \times \Pi_L)$$

where:

λ_p = failure rate (failures/10^6 hrs.)

λ_b = base failure rate

Π_E = environmental factor

Π_C = contact form factor

Π_{CYC} = cycling factor

Π_L = stress factor

Isolating Π_E, and defining:

$$S = \lambda_b \times \Pi_C \times \Pi_{CYC} \times \Pi_L$$

yields:

$$\lambda_p = S \, \Pi_E$$

Six switches were contained in the prediction vehicles. Despite the apparent lack of data, the value of "S" as follows seems reasonable and, is, therefore utilized. The value of "S" was calculated for each switch and an average value of S was determined to be:

$$S_{AV} = .006$$

Using S_{av} as an estimator for S in the above equation,

$$\lambda_p = .006 \, \Pi_E$$

Ref. Table 5.1.11-4 of MIL-HDBK-217D for Π_E values.

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j. Miscellaneous Parts

Miscellaneous Parts include vibrators, quartz crystals, fuses, lamps, fiber optic cables and connectors, meters, circuit breakers, and microwave elements. The prediction vehicles contained quartz crystals, fuses, lamps, and circuit breakers. These are all assigned the fixed failure rates in accordance with Table 5.1.15-1 of MIL-HDBK-217D.

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k. Connections

Connections include wirewrap (ww-); solder (reflow lap to board) (csr); sol[illegible], wave to board (csw); hand solder (hsc); crimp (cmp); and weld (wld).

The basic failure rate model for connections is:

$$\lambda_p = \lambda_b \, (\Pi_E \times \Pi_T \times \Pi_Q)$$

where:

λ_p = failure rate (failures/10^6 hrs.)

λ_b = base failure rate

Π_E = environmental factor

Π_T = tool type factor

Π_Q = quality factor

The majority of the connections contained in the six prediction vehicles were csw (wave to board) type. Since there is such a vast difference between the λ_b's of connectors in general (Ref. Table 5.1.14-1 of MIL-HDBK-217D), the "W" value of the other types of connections (i.e., hsc, csr, and ww-) differ by orders of magnitude from the "W" values of the csw type. As a result, the "W_{av}" obtained from the data does not truly reflect the majority of the cases.

Therefore, the following procedure is suggested based on data and engineering judgement:

Naturally, if the actual type of connection is known, the appropriate λ_b from Table 5.1.14-1 of MIL-HDBK-217D and, in the case of crimp connections, the appropriate Π_T and Π_Q from Tables 5.1.14-3 and 5.1.14-4 of MIL-HDBK-217 should be used. However, when the particular connection type is unknown, the wave to board (csw) should be assumed.

Then:

$\Pi_T = 1$

and

$\Pi_Q = 1$

The above formula becomes:

$\lambda_p = \lambda_b \Pi_E$ or

equivalently

$\lambda_p = W\Pi_E$

However: $\lambda_b = W = .00029$ for csw type connections.

Therefore:

$$\lambda_p = .00029\ \Pi_E$$

Reference Table 5.1.14-2 of MIL-HDBK-217D for Π_E values.

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1. Printed Circuit Board Connectors

The basic formula for a printed board connector is:

$$\lambda_p = \lambda_b\ (\Pi_E \times \Pi_p \times \Pi_k)$$

where:

λ_p = failure rate (failures/10^6 hrs.)

λ_b = base failure rate

Π_E = environmental factor

Π_p = failure rate multiplier (based on number of pins)

Π_k = cycling rate factor

Isolating Π_E and defining:

$$P = \lambda_b \times \Pi_p \times \Pi_k$$

yields:

$$\lambda_p = P\ \Pi_E$$

The six prediction vehicles contained a total of 157 connectors. The value of "P" was caluclated for each connector and an average value of P was determined to be:

$$P_{AV} = .0046$$

Using P_{AV} as an estimator for P in the above formula,

$$\lambda_p = .0046\ \Pi_E$$

Ref. Table 5.1.12.1-6 of MIL-HDBK-217D for Π_E values.

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m. Printed Circuit Board

The failure rate model for a printed circuit board is:

$$\lambda_p = \lambda_b \times N \times \Pi_E$$

where:

λ_p = failure rate (failures/10^6 hrs.)

λ_b = base failure rate

N = number of plated through holes

Π_E = environmental factor

Isolating Π_E and defining:

$$B = \lambda_b \times N$$

yields:

$$\lambda_p = B\, \Pi_E$$

The six prediction vehicles contained a total of 199 boards. The value of "B" was calculated for each board and an average value of B was determined to be:

$$B_{AV} = .0035$$

Using B_{AV} as an estimator of B,

$$\lambda_p = .0035\Pi_E$$

Ref. Table 5.1.13 of MIL-HDBK-217D for Π_E values.

III. SUMMARY OF BALLPARK FAILURE RATE FORMULAS

As a result of the analysis, the following formulas are presented:

(Ref. appropriate tables of MIL-HDBK-217D or pages of this report for Π_E values)

a. Capacitors: $\lambda_p = .0026\ \Pi_E$ (Ref. page 4 of this report)

b. Resistors: $\lambda_p = .004\ \Pi_E$ (Ref. page 6 of this report)

c. Semiconductors:

(1) Diodes: $\lambda_p = .0016\ \Pi_E$ (Ref. Table 5.1.3.4-1)

(2) Transistors: $\lambda_p = .008\ \Pi_E$ (Ref. Table 5.1.3.1-1)

d. Relays: $\lambda_p = .069\ \Pi_E$ (Ref. Table 5.1.10-4)

*e. Integrated Circuits: $\lambda_p = .14 + .007\ \Pi_E$ (Ref. Table 5.1.2.5-3)

f. Inductors: $\lambda_p = .0009\ \Pi_E$ (Ref. Table 5.1.8.2-3)

g. Connectors: $\lambda_p = .021\ \Pi_E$ (Ref. Table 5.1.12.1-6)

h. Optical Devices: $\lambda_p = .07\ \Pi_E$ (Ref. Table 5.1.3.10-1)

i. Switches: $\lambda_p = .006\ \Pi_E$ (Ref. Table 5.1.11-4)

j. Miscellaneous Devices: (Ref. Table 5.1.15-1)

k. Connections: $\lambda_p = .00029\ \Pi_E$ (Ref. Table 5.1.14-2)

l. Printed Circuit Board Connector: $\lambda_p = .0046\ \Pi_E$ (Ref. Table 5.1.12.1-6)

m. Printed Circuit Board: $\lambda_p = .0035\ \Pi_E$ (Ref. Table 5.1.13)

NOTE: The specific Π_E factor for each particular part should be used. If the specific model is unknown, use that of a general purpose device (i.e., Group I for transistors, or Group IV for diodes).

This suggests that a "ballpark" failure rate estimate can be made knowning only the environment and number of particular part types in a system.

The General Ballpark Model can be expressed as:

λ_p (total) $= .0026\ N_1\ \Pi_{E(CAP)} + .004\ N_2\ \Pi_{E(RES)} + .0016\ N_3\ \Pi_{E(DIODE)} + .008\ N_4\ \Pi_{E(TRANSISTOR)} + .069\ N_5\ \Pi_{E(RELAY)} + (.14 + .007\ \Pi_{E(IC)})\ N_6 + .0009\ N_7\ \Pi_{E(IND)} + .021\ N_8\ \Pi_{E(CON)} + .07\ N_9\ \Pi_{E(OPT)} + .006\ N_{10}\ \Pi_{E(SW)} + \lambda_p(MISC) + .00029\ N_{11}\ \Pi_{E(CONN)} + .0046\ N_{12}\ \Pi_{E(PBC)} + .0035\ N_{13}\ \Pi_{E(PCB)}$ + any other failure rates not in the above.

*If the quality levels are known, use $\lambda_p = \Pi_Q\ (.047 + .0024\ \Pi_E)$ (Ref. Table 5.1.2.5-3 for Π_E values and Table 5.1.2.5-1 for Π_Q values).

where:

$$N = \sum_{i=1}^{13} N_i$$

Where

(N_i = # of components of kind i in system)

The following table provides a comparison of failure rate prediction results between the ballpark method described above and part by part detailed prediction results using ORACLE for the six systems used as study vehicles. For ease of comparison, failure rates (λ_p) have been converted to Mean-Time-Between-Failures (MTBF) since

$$MTBF = \frac{1}{\lambda_p} \text{ hours}$$

The results obtained were:

SYSTEM	# PARTS	ORACLE MTBF (hours)	BALLPARK FORMULA MTBF (hours)
A	1308	3,147	6,887
B	1376	12,032	4,525
C	334	17,734	33,333
*D	1579	1,029	16,313
E	5784	1,654	1,117
F	844	10,270	10,087

*System had many user supplied fixed failure rates, i.e., not calculated in accordance with MIL-HDBK-217.

IV. AVERAGE FAILURE RATE PER PART BALLPARK PREDICTION METHOD

Following a less constrained concept for a Ballpark Reliability Prediction procedure, failure rates for each component part in the six vehicles were calculated using ORACLE, a sum total failure rate was determined, and this was in turn divided by the total number of parts comprising the six vehicles. The result was an average failure rate per part (λ_{PAv})

where:

λ_{PAv} = .2 failures per million hours

The following table provides a comparison between the average failure rate per part Ballpark Prediction procedure described above and part by part detailed prediction results using ORACLE for the six systems used as study vehicles. For ease of comparison, λ_{PAv} is converted to an $MTBF_{AV}$, such that

$$MTBF_{AV} = \frac{1}{\lambda_{PAv}} \text{ hours}$$

SYSTEM	# PARTS	ORACLE MTBF (hours)	BALLPARK PREDICTION AVERAGE MTBF (hours)
A	1308	3,147	3,823
B	1376	12,032	3,634
C	334	17,733	14,970
D	1579	1,029	3,167
E	5784	1,654	864
F	844	10,270	5,925

V. TRIAL APPLICATION

Two electronics communications systems whose data was not part of this analysis were evaluated according to:

1. ORACLE, a "full blown" reliability prediction according to MIL-HDBK-217.

2. The MIL-HDBK-217 Parts Count Prediction Technique, a procedure which, while less complicated, still requires substantial data about the parts making up the system (Ref. Section 5.2 of MIL-HDBK-217D).

3. The Ballpark Formula Technique, requiring environmental information and a parts count for each type of part in the system (Ref. Sections II and III of this report).

4. Tne Ballpark Prediction (average failure rate per part) Technique, requiring only a total system parts count (Ref. Section IV of this report).

The following systems were evaluated:

SYSTEM	ENVIRONMENT	AMBIENT TEMPERATURE	NUMBER OF PARTS
1	*AIT	$70^{o}C$	769
2	*AIT/GM	$55^{o}C$-$73^{o}C$	4108

*AIT represents airborne inhabited transport, GM represents ground mobile environment.

The results obtained were:

SYSTEM	ORACLE MTBF	PARTS COUNT MTBF	BALLPARK FORMULA MTBF	BALLPARK AVERAGE MTBF
1	6333	3620	13,333	6490
2	2249	1831	2,222	1217

NOTE: All MTBF's are in units of hours

The results obtained from all three shortcut prediction methods all appear to be between one half and twice the value of the ORACLE prediction. One cannot necessarily conclude that one shortcut technique is better than the others. Therefore, a suggested procedure for using these techniques is:

(1) When no other data except for total parts count is available, use the Ballpark Average Technique based on .2 failures per million hours per part.

(2) When additional data such as environments and a parts breakdown are available, use the Ballpark Formula Technique and the Ballpark Average Technique, and then average the two results.

(3) When adequate data is available, the Parts Count Prediction Technique should be used in addition to the other two and an average of the three calculated.

(4) When detailed data concerning electrical stresses and operating conditions is available, a detailed analysis exercising the models contained within MIL-HDBK-217 should be performed.

Following (3) above, whereby calculating an average for the three shortcut methods, yields the following results:

SYSTEM	ORACLE MTBF	SHORTCUT AVERAGE MTBF
1	6333	7815
2	2249	1757

From this, one can see that the results are quite reasonable and "in the Ballpark". Therefore, the procedures described above have the potential for becoming a valuable tool for estimating reliability figures in preliminary phases of design and in the absence of detailed system operating characteristics. Future studies are being carried on to further validate and verify the results.

APPENDIX A

PART TYPE CODES

The following part type codes were utilized throughout this report.

CODE		PART TYPE
1	cap	capacitor
2	d--	diode
3	ic-	integrated circuit
4	pbc	printed circuit board connection
5	res	resistor
6	csr	reflow solder connection
7	ind	inductor
8	ry-	relay
9	zd-	zener diode
10	xr-	transistor
11	opt	optical device
12	pcb	printed circuit board
13	hsc	hand soldered connection
14	cbk	circuit breaker
15	ww-	wirewrap connection
16	csw	solder, wave to boards
17	inc	incandescent lamp
18	fus	fuse
19	xtl	quartz crystal
20	hyb	hybrid
21	sw-	switch
22	vd-	varacter giode
23	mis	miscellaneous

APPENDIX B

FAILURE RATE DATA

The following failure rate data was collected for each of the 6 systems:

1. SYSTEM A - GROUND FIXED ENVIRONMENT

PART TYPE	NUMBER	TOTAL FAILURE RATE	FAILURE RATE/PART
cap	299	6.889	.023
d--	54	.568	.0105
ic-	216	251.7	1.032
pcb	23	1.05	.0456
res	203	8.889	.0438
csw	366	.159	.0004
ind	2	.0537	.02685
ry-	118	.954	.814
zd-	167	.624	.4765
xr-	13	.633	.63
opt	12	28.32	2.36
mis	105	102.80	.98
	1308	420.61	.32

2. SYSTEM B - NAVAL SHELTERED ENVIRONMENT

PART TYPE	NUMBER	TOTAL FAILURE RATE	FAILURE RATE/PART
ic-	1306	54.7700	.0419
pcb	9	22.5300	2.5000
pbc	18	.9024	.0500
cap	33	1.8860	.0570
csr	9	2.7010	.3000
res	1	.3190	.3190
	1376	83.1100	.0604

3. SYSTEM C - GROUND MOBILE ENVIRONMENT

PART TYPE	NUMBER	TOTAL FAILURE RATE	FAILURE RATE/PART
ic-	74	7.546	.1020
pcb	13	.04904	.0004
cap	57	6.516	.1143
con	23	7.398	.3217
hsc	14	16.11	1.1507
inc	1	1.0	1.0000
res	130	.06679	.0005
fus	3	.3	.1000
ind	13	15.72	1.2092
ry-	6	1.686	.2810
	320	56.39	.1762

4. SYSTEM D - NAVAL SHELTERED ENVIRONMENT

PART TYPE	NUMBER	TOTAL FAILURE RATE	FAILURE RATE/PART
pcb	74	.09694	.00131
cap	367	296	.8065
d--	77	34.43	.447
fus	1	.1	.1
xr-	102	487.1	4.78
zd-	67	69.27	1.034
cbk	7	14.0	2.0
res	814	40.49	.0497
ic-	63	29.37	.466
xtl	1	.2	.2
hyb	2	.056	.028
pbc	4	.792	.198
	1579	971.905	.6155

5. SYSTEM E - AIRBORNE UNINHABITED FLIGHT ENVIRONMENT

PART TYPE	NUMBER	TOTAL FAILURE RATE	FAILURE RATE/PART
cap	2057	102.3	.0497
csw	63	61.30	.973
d--	470	27.01	.057
hyb	92	113.6	1.22
ic-	867	196.7	.227
pbc	128	3.215	.025
pcb	66	3.140	.048
res	1799	26.05	.0145
ry-	31	13.96	.450
xr-	76	23.95	.315
xtl-	23	4.582	.199
zd-	41	3.998	.098
opt	3	.4126	.138
cbk	2	4.000	2.0
con	54	11.46	.212
inc	4	4.000	1.0
sw-	6	3.405	.5675
vd-	2	1.452	.726
	5721	604.54	.1057

6. SYSTEM F - GROUND FIXED ENVIRONMENT

PART TYPE	NUMBER	TOTAL FAILURE RATE	FAILURE RATE/PART
cap	235	1.457	.0062
cbk	25	50.00	2.0
d--	22	.1846	.008391
pcb	14	.09893	.0070664
res	99	1.50	.01515
ww-	14	.02890	.0020642
zd-	1	.01200	.012
ic-	413	43.16	.1045
opt	1	.07410	.0741
con	26	.1115	.0043
csw	1	.0456	.0456
hyb	1	.396	.396
hsc	1	.234	.234
pbc	7	.1099	.0157
	844	97.39	.1154

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